

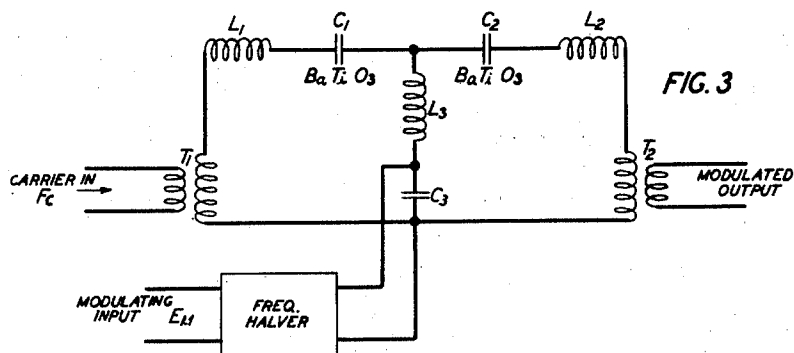
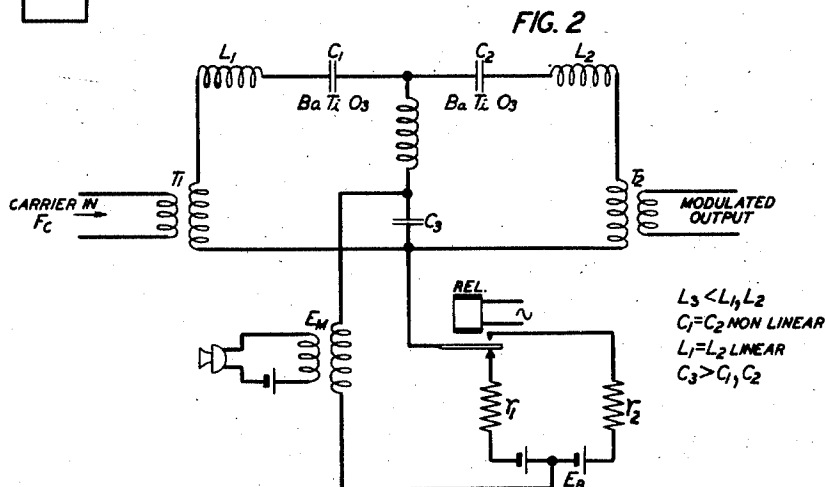
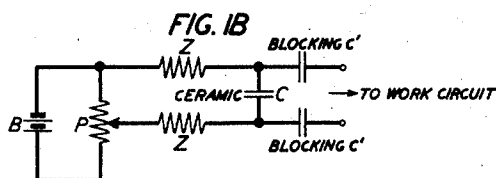
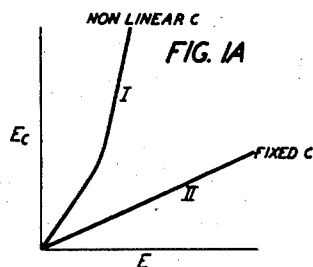
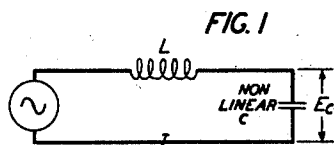
June 5, 1951

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NONLINEAR REACTANCE CIRCUITS UTILIZING
HIGH-DIELECTRIC CONSTANT CERAMICS

2,555,959

Filed Oct. 18, 1946

3 Sheets-Sheet 1



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3 Sheets-Sheet 2

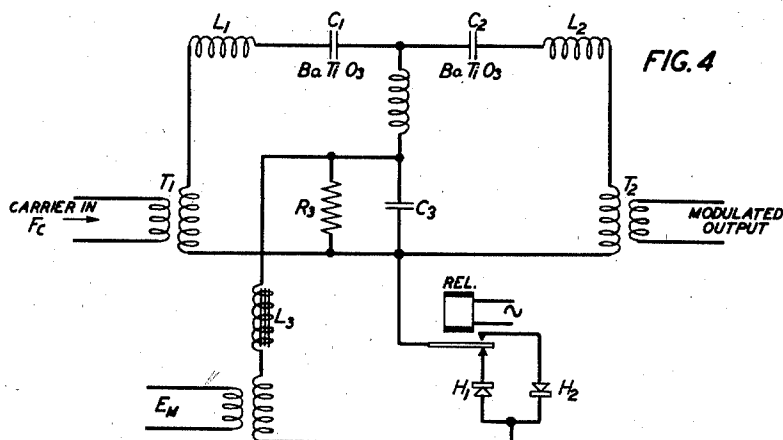


FIG. 4

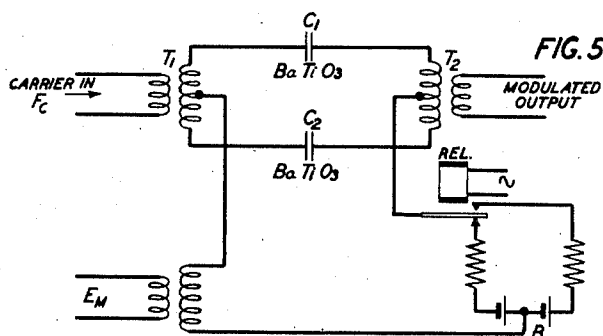


FIG. 5

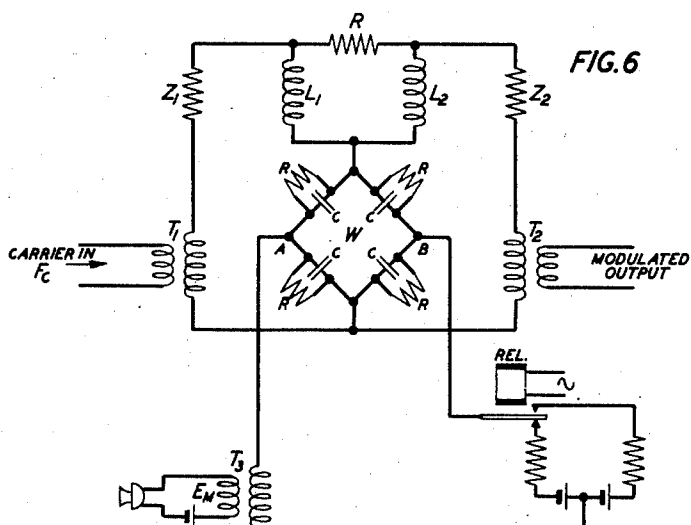


FIG. 6

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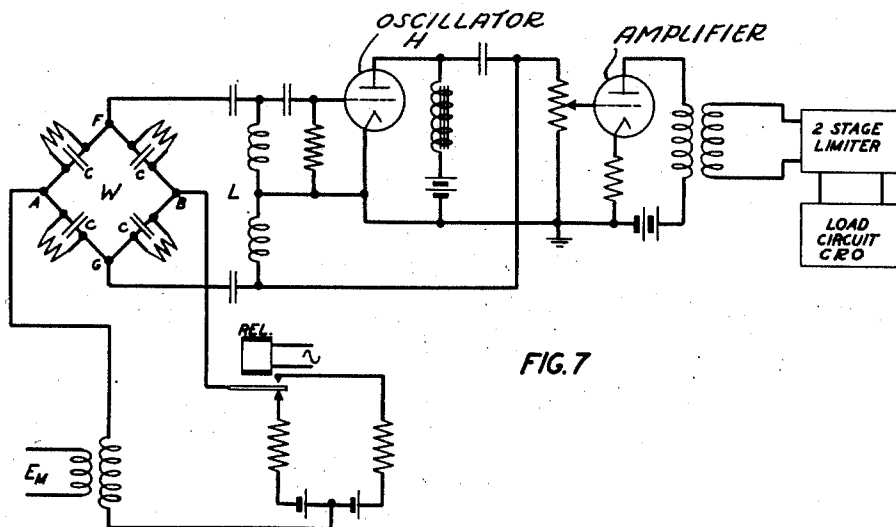


FIG. 7

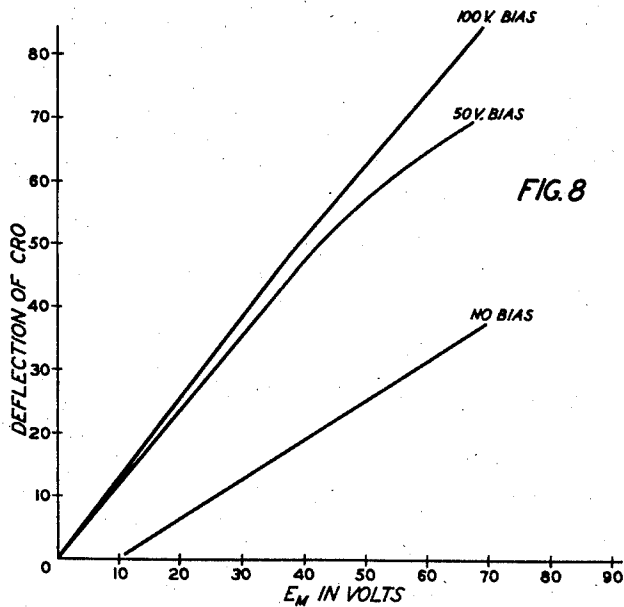


FIG. 8

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UNITED STATES PATENT OFFICE

2,555,959

NONLINEAR REACTANCE CIRCUITS UTILIZING HIGH DIELECTRIC CONSTANT CERAMICS

Austen M. Curtis, deceased, late of South Orange, N. J., by Lavalette Stevenson Curtis, executrix, South Orange, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application October 18, 1946, Serial No. 704,151

19 Claims. (Cl. 332—30)

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This invention relates to voltage-dependent capacitances and to circuits utilizing such capacitances.

One object of this invention is to apply ceramics of high and variable dielectric constant to communication circuits and the like.

Another object of this invention is to provide compact, stable, non-linear capacitances.

A further object is to improve the operation of frequency, amplitude and phase-modulators that make use of voltage-dependent capacitances.

A feature of the invention is the provision of electrostatic field biasing for ceramic condensers characterized by high and variable dielectric constant.

Another feature of the invention is the provision of a direct current biasing potential of reversible polarity for titanate condensers of high dielectric constant.

Another feature of the invention is a reactance utilizing ceramic condensers of high dielectric constant possessing a non-linear voltage-charge characteristic.

Another feature of the invention comprises automatically controlled oscillatory and resonant circuits which utilize ceramic condensers of high and variable dielectric constant.

More specific features of the invention are frequency modulation, amplitude modulation, and phase-modulation circuits characterized by voltage variation of the capacitance of a barium titanate condenser.

The present invention makes use of ceramics of high and variable dielectric constant, notably, barium titanate and the like, which in accordance with the invention, have been found to possess optimum properties adapting them to the objectives thereof.

Ceramics in general may be defined as inorganic oxides or their mixtures fired to a high temperature such as 400° C. or more, whereby a hard, durable substance (ceramic) is formed, which may be crystalline, or amorphous in nature. Examples thereof are glass, porcelain, steatite and the titanates.

Materials of high dielectric constant and low loss, effective over a wide range of frequencies and operable at ordinary temperatures are highly desirable in the communications field. Rutile, a naturally occurring form of titanium dioxide, and also the chemically formed titanium dioxide are well known in the art and are characterized by a low loss and a dielectric constant ϵ of approximately 100.

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In the highest known range of dielectric constant, namely, $\epsilon=1,000$ to 10,000, the only known substances are apparently Rochelle salts of the ordinary and heavy hydrogen types, and a ceramic, namely barium titanate or its mixture with strontium titanate.

Titanates of the metals of the second periodic group may be divided into three main classes according to the magnitude of their dielectric constants. The first class, characterized by $\epsilon < 100$ embraces the titanates of magnesium ($\epsilon=17$), zinc ($\epsilon=30$), cadmium ($\epsilon=62$), beryllium ($\epsilon=70$). The second class having $100 < \epsilon < 1,000$ includes the titanates of calcium ($\epsilon=115$) and strontium ($\epsilon=155$). The third class with $\epsilon > 1,000$ includes barium titanate and its mixture with strontium titanate. The values of the dielectric constants appearing in the parentheses are for room temperatures and a frequency of about a megacycle. The dielectric constant ϵ for each of the classes in general increases with increasing electronic polarizability of the metallic ion. For titanates such as barium, calcium and strontium, which form crystal lattices of the perovskite type, the dielectric constant increases with the distance between the centers of the oxygen and titanium ions, and reaches especially high values in barium titanate.

In the specification, the term "non-linear condenser" may be defined as characterized by a non-linear relation between applied voltage and charge.

In accordance with the invention, it has been found that the direct current capacity of ceramic condensers, and in particular, barium titanate condensers, is dependent on the applied voltage, increasing with voltage non-linearly and by large percentages, and that its effective capacity to alternating currents shows a similar variation. Also, it has been found in accordance with the invention, that the performance of barium titanate condensers or the like in low and high frequency circuit applications may be considerably improved by a direct current bias, and more particularly by applying a bias that intermittently reverses in polarity.

Circuits developed in accordance with the invention which includes barium titanate condensers or the like of high dielectric constant i. e., $\epsilon > 1,000$, are characterized by simplicity, compactness and exceptional stability with respect to mechanical, physical, chemical and thermal variation. In particular, these circuits provide in the communications field improved forms of non-linear reactances, sensitive controllers of

impedance, and automatic tuners, which may be varied by the voltage control of the high capacitance of said titanate condensers.

More particularly, circuits in accordance with the invention utilizing titanate condensers of high dielectric constant $\epsilon > 1,000$, are capable of providing frequency, phase and amplitude modulation at ordinary temperatures and over a wide range of frequency. When an alternating current carrier and a modulating voltage of considerably lower frequency are applied simultaneously to a ceramic condenser of barium titanate or the like, the effective capacity thereof to the carrier varies with the modulating voltage. The amplitude, frequency and wave form of the modulating output depend not only upon the modulating input, but upon whether or not a polarizing voltage is applied to the condensers and on how long it has been applied. This variation with time is undesirable. The polarizing voltage or bias is reversed at frequent intervals in accordance with the invention and thereby the undesirable effect is minimized and stable performance and improved characteristics for the modulator result.

In some exemplary cases, useful variations of the capacity have been produced with a carrier wave of 52 kilocycles per second and modulating frequencies from 10 to 7,000 cycles per second and modulating voltages as low as 2.5 volts.

The relation between modulating voltage and ΔC (the capacity variation of the barium titanate condenser) is nearly linear up to an input determined by the polarizing, direct current voltage.

The relation between modulating frequency and ΔC , with a carrier of 36 kilocycles, is practically flat to 2,000 cycles per second and only down 6 decibels at 4,000 cycles per second. When the carrier is raised to 49 kilocycles, the flatness of the characteristic improves and the sensitivity to modulation increases.

The sensitivity to a modulating voltage is increased in direct proportion to a decrease in the thickness of the dielectric, being proportional to the applied voltage per unit thickness. The variation in the dielectric constant depends upon the potential gradient in the dielectric. Thus the voltage necessary to get any given per cent variation in capacity would be proportional to the thickness of the dielectric.

Fig. 1 shows a voltage-controlled resonant circuit in accordance with the invention;

Fig. 1A shows a non-linear response characteristic;

Fig. 1B shows a voltage-controlled impedance for insertion in alternating current circuits;

Figs. 2, 3, 4 and 6 show various forms of modulation circuits in accordance with the invention;

Fig. 5 shows a balanced modulation circuit;

Fig. 7 shows a frequency modulation circuit;

Fig. 8 shows graphs illustrating the effects that the bias on a barium titanate condenser has on the frequency modulated output.

The circuit illustrated in Fig. 1 represents a voltage-controlled resonant circuit, utilizing a non-linear condenser of barium titanate or the like for automatic tuning thereof. The circuit comprises an inductance coil L in series with a ceramic condenser C of barium titanate. The input voltage E is applied from an alternating current source at a frequency somewhat lower than that to which the LC combination is resonant at a low voltage.

The voltage response characteristic of barium titanate is such that as E is raised, the dielectric

constant thereof increases, causing C to increase its effective capacity, bringing L and C more nearly into resonance. In this manner, self-tuning by voltage control is obtained. As illustrated graphically in Fig. 1A, (curve I) E_c , the voltage across the barium titanate condenser, and I , the current in the resonant LC circuit, increase more rapidly than E . This demonstrates that the barium titanate condenser has a non-linear response characteristic in contradistinction to the linear characteristic of conventional condensers illustrated by curve II. If the circuit resistance R of the LC combination is low enough, the transition into resonance occurs abruptly at a certain critical voltage.

In an exemplary case involving a single-frequency applied current of about 1,000 cycles per second, the effective capacity of C , as judged by its resonance with a fixed inductance L , increased about 20 per cent as the applied voltage was increased from 10 to 100 volts R. M. S.

When barium titanate of about 25 mil thickness is used as the dielectric of a practical sized condenser, it has been found that the apparent capacity when such condenser is used in a tuned circuit increases about 100 per cent when 300 volts peak of a single frequency voltage is applied, at least for the lower frequencies.

A simple voltage-controlled circuit utilizing a barium titanate condenser is shown in Fig. 1B. The circuit permits fine changes in impedance under the control of a smoothly varied direct current voltage. The circuit is balanced and comprises a pair of equal impedances Z and a shunting barium titanate condenser C which may be connected to some work circuit by means of symmetrically located blocking condensers C' . A potentiometer P provides a variable voltage from the battery B , whereby the dielectric constant and capacity of the barium titanate condenser C may be varied. The blocking condensers are much larger than the controlled ceramic condenser C , while the impedances Z are large enough to make their leakage negligible. The capacity of the condenser C may be varied over a considerable range and in very small increments, depending on how fine the potentiometer is.

The circuit illustrated in Fig. 2 represents a network utilizing a ceramic condenser of barium titanate or the like for producing phase and amplitude modulation of a carrier wave. In the network, two tuned circuit meshes C_1L_1 and C_2L_2 are coupled by a low inductance L_3 , the latter being in series with a relatively large blocking condenser C_3 for separating the carrier and the modulating voltages. The condensers C_1 and C_2 are non-linear ceramic condensers of barium titanate or its mixture with strontium titanate.

The carrier voltage F_c is applied at or near the resonant frequency of the network by means of a transformer T_1 at the position "carrier in" and modulation is observed in the output either directly or after demodulation. The modulating voltage E_m , which may represent e. g., voice signals as shown or keyed voice frequency telegraph signals is applied across the blocking condenser C_3 in series with direct current biasing voltage, which is automatically reversed in polarity for equal periods of one or more seconds. The biasing voltage is derived from a battery E_B or its equivalent and in combination with the alternating current signals F_c and E_m applied to the network, acts on the ceramic condensers

C_1 and C_2 to vary the capacity non-linearly, whereby an output modulated in amplitude and phase is produced.

The reversible polarity of the bias is produced by means of the relay REL, whose contact is switched between the positive and negative pole of the battery E_b at a desired rate. Resistances r_1 and r_2 are inserted in the battery circuit to control the rate of charge and discharge of the condensers C_1 , C_2 .

Instead of battery bias reversed at intervals by a relay, the bias may be derived from the plate circuit of a multivibrator (not shown), oscillating at low frequency.

The polarizing voltage may obviously also be applied in any other suitable manner to the ceramic condensers, such as in parallel with the modulating input, or the like, suitable impedance being connected in the circuit to prevent the battery from reducing the modulating input by an objectionable amount.

If the polarizing voltage is omitted then the principal modulated component of the output will be at twice the frequency of the modulating input current and the efficiency of the modulation will be considerably reduced.

It should be understood that various modifications may be made in the circuit of Fig. 2, for example, the number of meshes may be increased or the coupling between the LC circuits may be wholly inductive instead of capacitive.

The circuit shown in Fig. 3 is a modification of that illustrated in Fig. 2, which is also adapted to produce phase and amplitude modulation. Its principal difference over the circuit of Fig. 2 resides in the inclusion of a frequency halver of the type disclosed in the United States patent, of R. L. Miller, 2,159,595 issued May 23, 1939, in the path between the modulating input currents and the non-linear, barium titanate condensers C_1 and C_2 . The use of a frequency halver circuit as a substitute for the biasing of the condensers C_1 , C_2 is preferred where the modulating signal current is of a single frequency or a number of single frequencies distributed over an octave or the like. Intelligible speech modulated on a carrier has been transmitted by utilizing the frequency halver construction of Fig. 3.

The modification illustrated in Fig. 4 is a variation of the form shown in Fig. 2, wherein the coupling between the meshes L_1C_1 and L_2C_2 is capacitive and is effected by means of condenser C_3 . A choke coil L_3 in the modulating input serves to separate the carrier and modulating paths. Instead of polarizing the non-linear, barium titanate condensers C_1 and C_2 by battery as disclosed in Fig. 2, the modulating alternating current signals are rectified by means of half-wave rectifiers H_1 , H_2 which greatly reduce but do not eliminate the undesired double frequency component aforementioned in the modulated output. This is due to the application of only one polarity to the condensers C_1C_2 by the rectifiers H_1 , H_2 .

In order to prevent the direct current component of the rectified modulating signal from producing in the condensers C_1C_2 an absorbed opposing voltage, it is necessary to reverse the direction of connection of the rectifiers to the ceramic condensers C_1C_2 at frequent and equal intervals by means of the switching relay. A suitable limit to the range of impedances into which the rectifier works may be provided by

the shunt resistance arm R_3 of the coupling condenser C_3 .

The circuits of Figs. 2, 3 and 4 require that the carrier frequency be many times as high as the highest modulating frequency to give a reasonably flat relation between the carrier F_m and the modulated output. This is due to the simple method shown of separating carrier and modulating paths. In circuits such as these, amplitude and phase modulation have been produced with modulating frequencies of 300 cycles per second and with carriers up to 5,000 cycles per second in some exemplary embodiments thereof. A more effective separation of the carrier and modulating paths is possible if the non-linear condensers and their associated circuit components are arranged so that there is a balanced relation between the carrier terminals and the modulating terminals.

Fig. 5 illustrates a circuit modification for producing phase and amplitude modulation, wherein a more effective separation of the carrier and modulating paths is accomplished by means of a balanced relation between the carrier terminals and the modulating terminals. In this modification, the entire modulating voltage E_m is applied to both barium titanate condensers C_1 and C_2 . The capacitances of these condensers is so chosen as to tune the leakage reactance of input and output transformers T_1 and T_2 respectively, whereby a low loss is presented to the carrier wave when the condensers are not acted on by a modulating input applied at E_m . The biasing voltage derived from the battery B is reversed at intervals by a polar relay operated by a low frequency alternating current source or the like in the manner described for Fig. 2.

The circuit shown in Fig. 6 represents a modification for producing amplitude and phase modulation by means of a mesh network of the type described in United States Patent 1,897,639, issued February 14, 1933, to J. G. Kreer, Jr., as modified to include a Wheatstone bridge of four equal non-linear, barium titanate condensers arranged as shown in Fig. 6. In this circuit, the inductances L_1 and L_2 are equal, while the capacitance C and shunting resistance R are so chosen as to give a maximum transmission loss to a current of frequency slightly different from that applied, which may be chosen so that it is on the slope of the transmission loss curve when the condensers are unmodulated.

Application of voltage to the corners A, B, of the Wheatstone bridge W (conjugate to those connected to inductances L_1 , L_2 , and the common conductor) will then cause variation in the phase and amplitude of the carrier wave in impedance Z_2 . The battery shown in Fig. 6, reversed at intervals by means of the relay REL supplies a polarizing voltage to the condensers C of the Wheatstone bridge W. Each of the equal condensers C is shunted by the same high resistance R to insure the even and rapid distribution of the electric charge thereon. The corners A, B, of the Wheatstone bridge W or the modulating input transformer T_3 may be shunted by any impedance or network capable of producing a desired relation between the frequency of the modulating voltage input and the voltage applied to A, B.

In one practical embodiment of the circuit shown in Fig. 6, a carrier of 10,000 cycles per second was modulated at successively different frequencies up to a frequency of about 5,000 cycles per second. As the modulating frequency ap-

proached that of the carrier, the submultiple, the sum and difference frequencies became strong in the modulated output.

Circuits of the type previously described are also capable of modulating the capacitance of non-linear barium titanate condensers or the like at considerably higher frequencies than those disclosed in the exemplary embodiments. Direct current biasing of the ceramic condensers of high dielectric constant $\epsilon > 1,000$ is desirable for good operation at both low and high frequencies, and reversing the polarity of the bias causes an appreciable improvement in the nature of the modulated products.

Fig. 7 illustrates a circuit for frequency modulating an oscillator by variations in the capacitance of non-linear barium titanate condensers contained in the frequency control circuit thereof. The oscillator H is a well-known Hartley type oscillator controlled by a Wheatstone bridge W of four equal condensers C of barium titanate or the like in the arms thereof. The modulating input E_m is applied to the Wheatstone bridge at one pair of corners A, B thereof and the oscillator H is connected to a conjugate pair of corners F, G thereof. The biasing battery arrangement is like that shown in Fig. 6. The oscillator H is followed by a buffer amplifier, and a two-stage limiter to remove any amplitude modulation appearing in the output of the amplifier. The limiter is followed by a load circuit which includes a cathode ray oscillograph CRO, on which the data of Fig. 8 are measured.

Referring to the graphs shown in Fig. 8, three curves are presented showing the relationship between the frequency modulated output and the 1,000 cycles per second modulating voltage in the circuit of Fig. 7 for the cases where (1) no bias, (2) 50-volt bias, (3) 100-volt bias are applied to the barium titanate condensers, the two latter being reversed in polarity once a second.

With no bias present on the condensers C, the output is $2F_m$ with a weak component of F_m . With the 50 and 100 volts bias, the output is a reasonably good sine wave up to the region where the modulating voltage exceeds the bias and the curve bends over.

Different configurations of the condenser bridge W shown in Fig. 7 may be used without changing the essential operation of the modulator circuit. For example, two of the bridge arms may be replaced by equal resistances or inductances. In this case each of the condensers C may be changed in size to avoid changing the oscillator frequency.

Although the ceramic titanate condensers have been mainly disclosed as elements of LC circuits, it should be understood that they may also be used in RC networks to produce phase and amplitude modulation of a carrier passing through the network in response to a modulating signal applied to the barium titanate condenser or the like.

What is claimed is:

1. A phase and amplitude modulator comprising a source of carrier waves, a source of modulating waves, a coupled two-mesh network, the coupling therebetween including a ceramic condenser of high dielectric constant, a constant voltage bias on said condenser, said condenser being connected to said modulating source and adapted to have its capacitance varied non-linearly and means for reversing the polarity of said bias at recurrent intervals.

2. A non-linear reactance comprising a con-

denser, a source of direct current voltage connected to bias said condenser, means for applying an alternating voltage to said condenser, and means for reversing the polarity of said direct current voltage at a desired rate to stabilize the operation thereof under said alternating voltage.

3. The structure of claim 2, wherein said condenser is ceramic and its reactance is non-linear with voltage.

4. A reactance comprising a non-linear ceramic condenser of high dielectric constant, a source of direct current voltage connected to said condenser for biasing it, and means for reversing the polarity of said bias at intervals to enhance the stability of operation of said non-linear condenser under alternating current potentials.

5. The structure of claim 4, wherein said condenser includes a titanate of the metals in the second group of the periodic system, and whose reactance is non-linear with voltage.

6. A reactance comprising a ceramic condenser of high dielectric constant greater than 100, the capacitance thereof being non-linear with respect to voltage, means for applying an electrostatic field thereto and means for reversing the field at intervals, whereby the performance characteristics of said condenser is stabilized.

7. A non-linear reactance comprising a condenser of barium titanate, a biasing source of direct current voltage connected to said condenser, and means for reversing the polarity of the said bias at intervals to stabilize said condenser.

8. A modulator comprising a source of carrier waves, a modulating source, a reactance circuit including a non-linear ceramic condenser of high dielectric constant coupled to said sources, means for applying a bias voltage to said condenser, and means for reversing the polarity of said bias voltage at intervals whereby the modulator is stabilized.

9. The structure of claim 8, wherein the condenser has a dielectric constant greater than 1000.

10. The structure of claim 8, wherein said reactance circuit comprises a pair of coupled tuned circuits, each thereof including said ceramic condenser.

11. The structure of claim 10, wherein the coupling between said tuned circuits is connected to said modulating source and said bias reversing means.

12. A circuit comprising a source of carrier waves, a modulating source, a modulator circuit comprising an alkaline earth titanate condenser of high dielectric constant connected to said sources, the capacitance of said condenser being varied non-linearly by said modulating source, and means for applying a bias of reversible polarity to said condenser at recurrent intervals to stabilize said modulator.

13. A reactance comprising a ceramic condenser of high dielectric constant, means for electrically biasing the same with a direct current potential, and means for reversing the polarity of said bias to stabilize the condenser.

14. A method of reactance control and stabilizing a non-linear ceramic having a dielectric constant in the range of 1000 or more comprising initially biasing by means of an applied electrostatic field, varying said field, and applying an alternating voltage to said substance.

15. A reactance comprising a ceramic condenser having a high dielectric constant which varies with voltage, means for applying a biasing direct current voltage thereto, and means for re-

versing the polarity of said bias at recurrent time intervals to stabilize said condenser.

16. A tuned circuit comprising an inductance and a ceramic condenser of high dielectric constant ϵ in the range of 1000 or greater, means for applying thereto a stabilizing uniform direct current field, a source of alternating current frequencies applied thereto, and means for varying the applied direct current voltage to provide sharp resonance of said tuned circuit.

17. The structure of claim 8, wherein said biasing means is a rectifier for said modulating signal and said reversing means is adapted to reverse polarity at equal intervals of time.

18. In combination, a frequency modulated oscillator having a non-linear condenser comprising a substance of perovskite lattice type having a high dielectric constant connected in frequency controlling relation thereto, and a modulating source connected to said condenser to vary the capacitance thereof, a biasing source of direct voltage connected to said condenser, and means for commutating the polarity of said bias to stabilize said condenser.

19. A variably tuned circuit comprising an inductance, a non-linear reactance comprising a ferro-electric dielectric of high dielectric constant and having a perovskite type lattice structure connected thereto, and automatic tuning means therefore comprising a direct current biasing source connected thereto and a potentiometer

therefor for varying the applied direct current bias, and means for reversing the polarity of said bias at intervals to stabilize said dielectric.

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5 *Executrix of the Estate of Austen M. Curtis, Deceased.*

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,012,710	Crosby	Aug. 27, 1935
2,032,620	Langmuir	Mar. 3, 1936
2,167,512	Jacobs	July 24, 1939
2,182,377	Guanella	Dec. 5, 1939
2,243,921	Rust et al.	June 3, 1941
2,306,555	Mueller	Dec. 29, 1942
2,349,811	Crosby	May 30, 1944
2,368,643	Crosby	Feb. 6, 1945
2,377,910	Wainer et al.	June 12, 1945
2,381,990	Stevens	Aug. 14, 1945
2,424,246	Mason	July 22, 1947
2,461,307	Antalek	Feb. 8, 1949
2,473,556	Wiley	June 21, 1949

OTHER REFERENCES

30 "Radio Engineers Handbook" by F. E. Terman, 1943, first edition, page 11. Published by McGraw-Hill Book Company.